NUTRIENT AND β_{17}-ESTRADIOL LOSS IN RUNOFF WATER FROM POULTRY LITTERS[1]

Brian E. Haggard, Paul B. DeLaune, Douglas R. Smith, and Philip A. Moore, Jr.[2]

ABSTRACT: A main water quality concern is accelerated eutrophication of fresh waters from nonpoint source pollution, particularly nutrient transport in surface runoff from agricultural areas and confined animal feeding operations. This study examined nutrient and β_{17}-estradiol concentrations in runoff from small plots where six poultry litters were applied at a rate of about 67 kg/ha of total phosphorus (TP). The six poultry litter treatments included pelleted compost, pelleted litter, raw litter, alum (treated) litter, pelleted alum litter, and normal litter (no alum). Four replicates of the six poultry litter treatments and a control (plots without poultry litter application) were used in this study. Rainfall simulations at intensity of 50 mm/hr were conducted immediately following poultry litter application to the plots and again 30 days later. Composite runoff samples were analyzed for soluble reactive phosphorus (SRP), ammonia (NH_4), nitrate (NO_3), TP, total nitrogen (TN) and β_{17}-estradiol concentrations. In general, poultry litter applications increased nutrient and β_{17}-estradiol concentrations in runoff water. Ammonia and P concentrations in runoff water from the first simulation were correlated to application rates of water extractable NH_4 (R^2 = 0.70) and P (R^2 = 0.68) in the manure. Results suggest that alum applications to poultry litter in houses inbetween flocks is an effective best management practice for reducing phosphorus (P) and β_{17}-estradiol concentrations in runoff and that pelleted poultry litters may increase the potential for P and β_{17}-estradiol loss in runoff water. Inferences regarding pelleted poultry litters should be viewed cautiously, because the environmental consequence of pelleting poultry litters needs additional investigation.
(KEY TERMS: water quality; poultry litter; nonpoint source pollution; nutrients; estradiol; best management practices.)

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INTRODUCTION

In the southwestern portion of the Ozark Plateaus (Arkansas, Missouri, and Oklahoma, USA), poultry farms are often concentrated within catchment boundaries and limited by suitable land available to spread poultry litter. Overall, forests generally dominate land use fractions in the Ozarks, but the percent of pasture may be as much as 90 percent in individual Ozark catchments. In the last decade, this region has been a leader in poultry production across the USA, as well as the focal point of many political and environmental controversies surrounding land application of poultry litter. The application of poultry litter to the landscape was based on forage nitrogen (N) needs, which often continues to be the dominant manure management technique. Emerging land and nutrient management strategies, such as P Risk Indices (Lemunyun and Gilbert, 1993; Gburek *et al.,* 2000), have recently considered P source factors and transport potential from the landscape. The shift to P-based management strategies has followed research showing the influence of poultry litter applications on P concentrations in surface runoff from pastures (e.g., Edwards and Daniel, 1992, 1993) and the link of elevated P concentrations in agricultural runoff to anthropogenic eutrophication of surface waters (Carpenter *et al.,* 1998).

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The agronomic and environmental effects of poultry litter application to pastures, forests, and row crops have been the focus of scientific investigation for the last decade. These efforts have often identified the buildup of P (and N to a lesser degree) in soils, resulting from the continual application of poultry litter (Sharpley *et al.,* 1993). Thus, investigations often focused on the relation between P concentrations in surface runoff from the landscape and soil test P content (Pote *et al.,* 1996, 1999). More recently, studies have shown that P concentrations in surface runoff were likely controlled by a combination of the amounts of water extractable phosphorus (WEP) in the applied poultry litters and the soil (Sauer *et al.,* 2000; McDowell and Sharpley, 2001). The amount of WEP in poultry litter applied to the landscape often explained a large proportion of the variation in runoff P concentration during small plot and rainfall simulation studies (DeLaune *et al.,* 2004; Kleinman *et al.,* 2002b; Vadas *et al.,* 2004). Water extractable application rates may be the controlling factor during the first few runoff events shortly after application whereas soil P has long term importance.

In the Ozarks, P concentrations in streams often increase with an increase in the proportion of pastures in the catchment (Haggard *et al.,* 2003). Much research has recently focused on factors affecting P release into surface runoff from the landscape (DeLaune *et al.,* 2004; Kleinman *et al.,* 2002a; McDowell and Sharpley, 2001). Other investigations have assessed the potential of on-farm best management practices such as vegetative buffer strips (Chaubey *et al.,* 1995) and chemical amendments to poultry litter (Moore *et al.,* 2000) to reduce P concentration and transport in runoff. The recent use of P-based management strategies on Ozark poultry farms has identified excess amounts of poultry litter in many catchments with concentrated poultry facilities (e.g., the Eucha-Spavinaw Basin in northeast Oklahoma and northwest Arkansas). Transport of raw or pelleted poultry litter to adjacent watersheds and even to row crop areas in the Mississippi Delta may be a potential option to alleviate the excess of poultry litter and shortage of available land.

Emerging concerns related to land application of poultry litter may revolve around antibiotic residuals and environmental estrogens because analytical methods have been improved to detect these compounds at very low concentrations in surface waters. Many of these chemicals are biologically active (e.g., β_{17}-estradiol) and may disrupt the endocrine system of wildlife and possibly even humans. Environmental estrogens have been associated with some physiological defects in fish and wildlife (Colborn *et al.,* 1993), and even human health concerns (Colborn *et al.,*1993; Sharpe and Skakkebaek, 1993; Davis and Bradlow, 1995). A recent survey of streams across the USA reported that 10 percent of the streams had measurable β_{17}-estradiol concentrations (< 0.1 mg/l; Kolpin *et al.,* 2002). The concentration of estrogenic compounds in poultry litter may be affected by bird gender and age (Shore *et al.,* 1993), and β_{17}-estradiol concentrations in runoff water from land receiving poultry litter often increase with an increase in application rates (Nichols *et al.,* 1997; Delaune *et al.,*2002). β_{17}-estradiol residuals have also been used to identify the influence of animal manures on ground water in the Ozarks (Petersen *et al.,* 2000).

It is likely that the solution to some catchment water quality management issues will require the transport of poultry litter to areas better suited for land application and that the poultry litter may need to be post-processed (i.e., pelleted, to facilitate economical transportation and use). To date, N, P, and β_{17}-estradiol transfer in runoff from pelleted poultry litters have not been evaluated on pastures in the Ozarks nor row crops in the Mississippi Delta. The overall objective of this investigation was to assess N, P, and β_{17}-estradiol concentrations in runoff water from small grass plots receiving various raw, chemically amended, and pelleted poultry litters applied at an equivalent total phosphorus (TP) rate. Specifically, (1) the use of $Al_2(SO_4)_3$ (alum) to reduce water extractable constituents in poultry litter and loss from the landscape, (2) the effect of pelleting poultry litter on water extractable constituents in the manure and loss in runoff from small plots, and (3) the relation between water extractable constituent application rates in poultry litters and runoff constituent concentrations from small plots were evaluated.

METHODS

The various poultry litters used in this study were collected or provided from two sources. Agri-Recycle, Inc. (Springfield, Missouri, USA) provided a source of raw poultry litter (hereafter, raw litter), pelleted composted poultry litter (hereafter, pelleted compost), and pelleted raw poultry litter (hereafter, pelleted litter). Pelleted compost and pelleted litter are commercially marketed as an organic fertilizer (Honey Crest Farms, Inc., Bentonville, Arkansas, USA); the poultry litter pellets were 3 to 5 mm in diameter and spherical to cylindrical in shape. The second source of poultry litters were collected from a local farm (see Moore *et al.,* 2000) and consisted of a source of raw poultry litter (hereafter, normal litter) and poultry litter from houses receiving alum applications at a rate of approximately 2 metric tons per 20,000 bird house (hereafter, alum litter). The unpelleted litters had small particles to large aggregate pieces of manure, unlike the pelleted litters which were more consistent in shape and size. Approximately 60 kg of alum litter was pelleted at a nearby pelleting plant (hereafter, pelleted alum). Thus, six poultry litters were used in this study. The various poultry litters were extracted for WEP, NO_3, and NH_4 using a 1:10 mass ratio of fresh, wet poultry litter to deionized water (Self-Davis and Moore, 2000). The Self-Davis and Moore procedure was used because this particular extraction ratio is widely used in Arkansas (e.g., see Sauer *et al.,* 2000; DeLaune *et al.,* 2004), but this procedure extracts only 20 to 30 percent of the total amount of WEP (Kleinman *et al.,* 2002b). Total phosphorus was determined using HNO_3 and H_2O_2 digestion and inductively coupled plasma (ICP) analysis (Zarcinas *et al.,* 1987). Poultry litters were also analyzed for TN by the University of Arkansas Analytical Soils Laboratory using a dry combustion method with a model 2000 LECO (St. Joseph, Michigan) CNS analyzer. Poultry litter analyses were conducted on three samples from each treatment.

At the University of Arkansas Agricultural Experiment Station, Fayetteville, Arkansas, USA, 28 small plots (1.5 m by 6.1 m) with a tall fescue (*Festuca arundincea* Shreb.), bermudagrass and clover mix on a Captina silt loam soil (fine silty, siliceous, active, mesic Typic Fragiudult) were selected. The plots were established in 1998 with a 5 percent slope and were hydrologically isolated using 0.15 m metal borders inserted vertically into the soil so that 0.05 m of the metal borders were above the soil surface. An Al trough at the downslope end was used to collect surface runoff. Small plot treatments included raw litter, pelleted litter, pelleted compost, normal litter, alum litter, pelleted alum, and no poultry litter application (control), with four replications of each treatment. Poultry litter treatments were applied at equivalent rates of manure TP, about 67 kg TP/ha, to the small plots using a completely randomized design. The poultry litters were applied at the same TP application rate because manure management strategies are starting to shift toward P-based applications over N-based applications. Total phosphorus based application would also demonstrate whether TP or WEP content of the poultry litters was the most important factor to consider in P transfer in runoff. All poultry litter treatments were hand spread evenly across the plot. One noticeable difference was that the unpelleted poultry litters appeared to dust the plot and leave the grass mixture slightly brown compared to the plots receiving pelleted litters where pellets generally fell to the soil surface or were caught in the grass mixture. Rainfall simulations were conducted immediately following land application of the various poultry litters in July 2002 and one month later in August 2002. Small plots received artificial rainfall at a rate of 50 mm/hr from large simulators using eight TeeJet 1/2HH-SS30WSQ nozzles (Spraying Systems, Wheaton, Illinois, USA) set approximately 3 m above the soil surface. The artificial rainfall continued until 30 minutes of continuous runoff was observed. Discrete runoff water samples were collected two minutes after initiation of runoff and every five minutes thereafter until 30 minutes of continuous runoff had elapsed. A single flow weighted composite runoff water sample was made from the six discrete samples from each plot and subsequently analyzed in the laboratory. Soil samples were collected from each plot (0 to 50 mm depth) before land application of the various poultry litters and also following the second rainfall simulations. The soils were dried at 80°C for at least 24 hours, sieved at 2 mm and then analyzed for Melich-3 soil test P (Mehlich, 1984). These plots had not received any manure or inorganic fertilizer applications since the summer of 2000, some two years earlier.

A small portion of the composite runoff water was filtered through a 0.45 µm membrane, then acidified with concentrated HCl to pH less than 2 to prevent NH_3 volatilization and P precipitation, and the acidified filtrate was analyzed for dissolved constituents (APHA, 1992). Soluble reactive phosphorus, NO_3, and NH_4 were determined colorimetrically using automated ascorbic acid reduction, cadmium/copper reduction (NO_3 plus NO_2, hereafter NO_3) and alkaline phenol, sodium hypochlorite, and nitroprusside reaction (NH_4). Total phosphorus was determined on an unfiltered, acidified portion of the composite runoff sample using HNO_3 and H_2O_2 digestion with ICP analysis (Zarcinas *et al.,* 1987). Total nitrogen was determined on an unfiltered, acidified portion of the composite runoff sample using a Skalar TN analyzer (Skalar Inc, the Netherlands). β_{17}-estradiol concentrations in runoff water were determined using enzyme linked immunosorbent assays (ELISA) on an unfiltered, unacidified water sample (Oxford Biomedical Research, Inc., Oxford, Michigan, USA).

Statistical analyses were performed using analysis of variance (ANOVA) and the software program Statistix 8.0 (Analytical Software, 2003). Constituent concentrations are often log-transformed to account for the log normal distribution of water quality data and to minimize the effect of outliers within the data (Hirsch *et al.,* 1991; Lettenmaier *et al.,* 1991). Manure nutrient content and runoff nutrient concentrations and loads were natural logarithm transformed, and means of ln transformed values were separated using Fisher's protected least significant difference (LSD). Simple linear regression was used to relate runoff nutrient concentrations and loads with manure total and water extractable nutrient application rates.

RESULTS

Nutrient Content of Various Poultry Litters

The various poultry litters had substantially different nutrient composition, particularly in the fraction of water extractable nutrients (Table 1). Total nitrogen content was not substantially different between the various poultry litters, except that alum litter had a greater total N content. Ammonia content was greatest in the alum litter, whereas pelleted alum levels were similar to the normal litter, and the other three treatments had the least but similar NH_4 content. NO_3 content was variable, ranging from less than 0.01 to 0.21 percent, with alum litter having the greatest content and normal litter the least. Overall, NO_3 content showed the greatest amount of variability between poultry litters.

Total phosphorus content was slightly different between treatments (1.36 to 1.91 percent) resulting in differences in the application rates of each poultry litter to achieve the desired application of approximately 67 kg TP/ha. Raw litter, pelleted litter, and pelleted compost generally had a greater amount of TP than did alum litter, pelleted alum, or normal litter (Table 1). The amount of WEP in the various poultry litters was significantly different, with pelleted litter and pelleted compost having two-fold and three-fold greater WEP content compared to raw litter and normal litter. Pelleted alum had about an eight-fold greater WEP content compared to alum litter and slightly less WEP than that in unprocessed poultry litters in this study. Overall, WEP content of these poultry litters was significantly different based on sources and treatments.

Soil Test Phosphorus, Rainfall and Runoff of Plots

Mehlich-3 soil test P (M3P) values before litter application in July 2002 was the same for all plots (Table 2). When M3P was measured one month after

TABLE 1. Mean Water Extractable and Total Nutrient Content of the Various Poultry Litters and Application Rate of the Various Poultry Litters.

Treatment	WEP+ (percent)	NO_3-N (percent)	NH_4-N (percent)	TN (percent)	TP (percent)	Dry Matter (percent)	TP-Based Poultry Litter Rate Applied (Mg/ha)	NH_4-N Rate Applied (kg/ha)	WEP Rate Applied (kg/ha)
Pelleted Compost	0.24 a	0.09 d	0.42 c	4.41 b	1.74 ab	92 a	4.2	17	9.2
Pelleted Litter	0.15 b	0.11 c	0.46 c	4.51 b	1.85 a	90 b	4.0	17	5.4
Raw Litter	0.07 c	0.16 b	0.46 c	4.37 b	1.91 a	83 d	4.3	16	2.6
Control	–	–	–	–	–	–	0.0	0.0	0.0
Alum Litter	0.02 f	0.21 a	1.60 a	5.19 a	1.36 d	75 e	6.5	80	0.7
Pelleted Alum	0.05 e	0.08 e	0.75 b	4.37 b	1.61 bc	84 c	5.0	32	1.9
Normal Litter	0.06 d	< 0.01 f	0.78 b	* cd	1.48 f	73	5.7#	35	2.8

Notes: The percent values are on a nutrient per dry weight poultry litter basis, and data shown is the mean of three replicates.
+Different letters within a column denote significant differences between water extractable and total constituents in the six litter treatments.
*Denotes TN analysis on normal litter was not completed before poultry litter was applied to plots.
#Denotes litter was applied based on an estimated 80 percent moisture and 6.2 Mg/ha should have been applied to meet the approximately 67 kg TP/ha desired application.

TABLE 2. Mean Mehlich-3 Soil P Content (M3P) and Hydrologic Characteristics of the Treatment Plots Used in the Artificial Rainfall Simulations.

				First Runoff Simulation				Second Rainfall Simulation			
Treatment	Initial+ M3P (mg/kg)	Final M3P (mg/kg)	ΔM3P (mg/kg)	Time to Runoff (min)	Rainfall (mm)	Runoff (mm)	Ratio of Rainfall to Runoff	Time to Runoff (min)	Rainfall (mm)	Runoff (mm)	Ratio of Rainfall to Runoff
Pelleted Compost	112 a	126 a	14 ab	24 a	45 a	6 a	0.14 a	10 b	33 b	15 a	0.44 a
Pelleted Litter	109 a	140 a	31 a	28 a	48 a	4 a	0.08 a	8 b	32 b	10 a	0.32 a
Raw Litter	120 a	127 a	7 b	39 a	57 a	3 a	0.07 a	18 a	40 a	13 a	0.32 a
No Poultry Litter	108 a	104 a	-4 b	24 a	45 a	6 a	0.13 a	9 b	33 b	15 a	0.45 a
Alum Litter	124 a	123 a	-1 b	34 a	53 a	4 a	0.08 a	12 b	35 b	11 a	0.21 a
Pelleted Alum	122 a	127 a	5 b	22 a	43 a	5 a	0.11 a	8 b	31 b	10 a	0.31 a
Normal Litter	107 a	120 a	13 ab	22 a	43 a	7 a	0.16 a	7 b	312 b	12 a	0.40 a

Notes: Data represent mean of four replicates.
+Different letters within a column denote significant differences between treatment plots

poultry litter application, a significant increase in M3P was observed in the plots (paired T-test, $p < 0.01$). The addition of ~67 kg TP/ha to each plot in the form of poultry litter resulted in an average increase of 12 mg M3P/kg in each plot; two rainfall simulations and one large natural event likely moved manure WEP into the soil, resulting in the significant increases. Pelleted litter, pelleted compost, and normal litter showed similar increases in M3P between treatments. Only pelleted litter had a significantly greater increase (ΔM3P). The control plots had similar average soil test P content in July 2002 (108 mg M3P/kg soil) and August 2002 (104 mg M3P/kg soil).

Runoff began within 7 to 39 minutes for each of the treatments during the first and second rainfall simulation, although the raw litter plots had the greatest mean time to runoff (18 minutes) in the second simulation which resulted in the greatest amount of rainfall (40 mm) to these plots in the second simulation (Table 2). Runoff from the plots was highly variable within treatments but mean runoff was similar between treatments, ranging from 3 to 7 mm and 10 to 15 mm during the first and second rainfall simulations, respectively. Overall, the mean ratio of runoff to rainfall from plots was similar between treatments during the first and second rainfall simulation. However, the ratio was much greater during the second simulation than during the first simulation.

Phosphorus Concentrations in Runoff Water

During the first rainfall simulation, runoff P concentrations from the small plots were dominated by SRP, accounting for greater than 90 percent of TP concentrations from pelleted compost, pelleted litter, raw litter, and normal litter, as well as plots without litter application (Table 3). The fraction of TP as SRP from plots receiving alum litter (71 percent) and pelleted alum (84 percent) was less than from the other treatments. The fraction of TP as soluble P was more similar between treatments during the second rainfall simulation (84 to 88 percent).

Some distinct differences in SRP and TP concentrations of runoff emerged between treatments during the rainfall simulations (Table 3). The plots without poultry litter application had the least P concentration in the runoff whereas plots receiving the various poultry litters had 3-fold to 18-fold greater SRP and TP concentrations during the first rainfall simulation. Of the plots receiving litter, alum litter had the least SRP and TP concentrations in runoff during the first

TABLE 3. Nitrogen and Phosphorus Concentrations in Runoff Caused by Two Artificial Rainfall Simulations on Small Plots Receiving Various Poultry Litter Treatments.

Treatment	SRP+ (mg/l)	TP (mg/l)	NO_3-N (mg/l)	NH_4-N (mg/l)	TN (mg/l)
First Runoff Event					
Pelleted Compost	16.2 a	18.1 a	1.6 abc	20.4 bc	60.8 a
Pelleted Litter	12.0 ab	12.5 ab	0.4 c	15.9 cd	40.1 a
Raw Litter	7.1 b	7.2 b	1.1 ab	9.0 d	15.5 b
No Poultry Litter	1.1 d	1.1 d	0.1 bc	BDL e	BDL c
Alum Litter	3.1 c	4.4 c	0.2 c	38.3 ab	50.3 a
Pelleted Alum	8.1 b	9.6 ab	0.4 bc	35.4 a	58.5 a
Normal Litter	15.1 a	16.3 a	7.3 a	22.0 abc	42.2 a
Second Runoff Event					
Pelleted Compost	1.3 ab	1.5 a	1.3 ab	0.16 b	1.3 a
Pelleted Litter	1.6 a	1.8 a	1.6 a	0.15 b	1.4 a
Raw Litter	1.5 ab	1.7 a	1.5 ab	0.20 ab	1.3 a
No Poultry Litter	0.6 d	0.7 c	0.6 d	0.15 b	0.8 b
Litter Alum	0.8 c	1.0 b	0.8 c	0.24 a	1.4 a
Pelleted Alum	1.1 bc	1.3 ab	1.1 bc	0.17 ab	1.2 a
Normal Litter	1.5 a	1.8 a	1.5 a	0.17 ab	1.2 a

Notes: Data represent mean of four replicates.
BDL denotes below detection limits.
+Different letters within a column for a runoff event denote significant differences between nutrient concentrations.

rainfall simulation, whereas the pelleted litter, pelleted compost, and normal litter treatments generally had the greatest SRP and TP concentrations. Pelleted compost and pelleted litter plots had P concentrations approximately 2.3-fold and 1.7-fold greater than the raw litter plots, and the pelleted alum plots had P concentrations greater than the alum litter plots. Runoff from plots receiving normal litter had SRP and TP concentrations 4.8-fold and 3.7-fold greater than runoff from the alum litter plots. Soluble reactive phosphorus (R^2 = 0.68, p = 0.02) and TP (R^2 = 0.68, p = 0.02) concentrations in the runoff were positively correlated to the amount of WEP applied in the various poultry litters to the plots during the first rainfall simulation (Figure 1). This showed that application rates of WEP in the various poultry litters explained 62 percent of the variation in cumulative SRP or TP load from the small plots during the rainfall simulations.

Fewer significant differences were observed during the second rainfall simulation, although alum litter generally had the least SRP and TP concentrations in runoff (Table 3). An 1,100-mm rainfall event occurred in Northwest Arkansas less than a week before the second simulation, likely contributing to the substantially reduced P (and N) concentrations in runoff water. Cumulative P transfer in runoff from the plots during the rainfall simulations were variable but generally showed similar differences to that observed in P concentrations (Table 4).

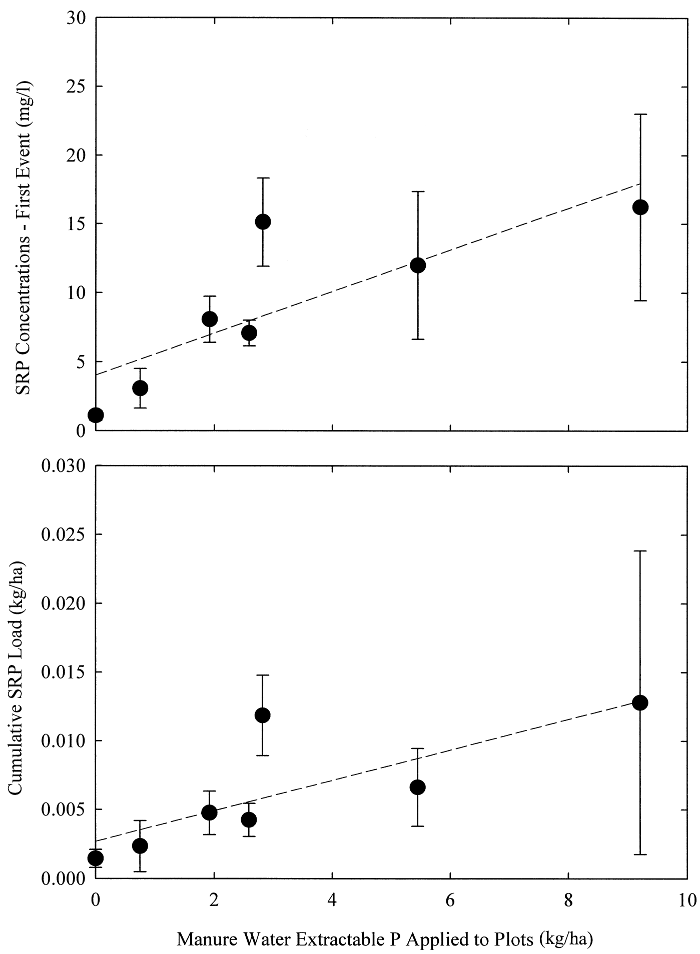

Figure 1. Effect of Application Rate of Water Extractable Phosphorus in the Various Poultry Litters on Phosphorus Concentrations (top) and Cumulative Load (bottom) in the Runoff from the Rainfall Simulations.

Nitrogen Concentrations in Runoff Water

The soluble fraction of TN measured in runoff was highly variable between treatments, ranging from 38 to 100 percent (Table 3). Most N transfer in runoff from plots without poultry litter application was in the form of NO_3, whereas most N transfer in runoff from plots receiving pelleted compost (62 percent) and pelleted litter (57 percent) was in the organic form during the first rainfall simulation. Of the poultry litter treatments, alum litter and pelleted alum had the greatest amount of N transferred in runoff in the form of NH_4 (76 and 61 percent) during the first rainfall simulation. During the second rainfall simulation, N transfer in runoff from all poultry litter treatments was almost entirely in the form of NO_3 (Table 4).

Several distinct differences in dissolved inorganic N and TN concentrations were observed between treatments during the rainfall simulations (Table 3). NO_3 concentrations in runoff water were greatest from plots receiving raw litter, normal litter, and pelleted compost during the first rainfall simulation, whereas NO_3 concentrations from the other treatments were not significantly different from plots without any poultry litter application. Ammonia concentrations were below detection limits in runoff water from plots without any poultry litter application. The greatest NH_4 concentrations were observed in runoff water from the normal litter, alum litter, and pelleted alum treatments during the first rainfall simulation. Ammonia concentrations were two orders of magnitude less in runoff water from plots receiving the various poultry litters during the second rainfall simulation. Total nitrogen concentrations were variable within treatments, and few significant differences were observed between treatments. Similar to P concentrations, NH_4 concentrations in runoff water during the first rainfall simulation were positively correlated ($R^2 = 0.70$, $p = 0.02$) to the application rate of water extractable NH_4 in the various poultry litters (Figure 2). This study showed that water extractable NH_4 application rate explained only 60 percent of the variation in cumulative NH_4 loads from the small plots (Figure 2). Differences in cumulative N loads from the small plots during the rainfall simulations were generally similar to that observed in N concentrations, although fewer significant differences between treatments were observed (Table 4).

β_{17}-Estradiol Concentrations in Runoff Water

β_{17}-estradiol concentrations in runoff water were highly variable from the pelleted compost and pelleted litter treatments, which numerically had the greatest average concentrations (Figure 3). Raw litter had the least concentration of the various poultry litter treatments. Overall, the pelleted poultry litter treatments and normal litter had the greatest β_{17}-estradiol concentrations in runoff water from the small plots during the first rainfall simulation. However, one month later β_{17}-estradiol concentrations were not significantly different between any of the various poultry

TABLE 4. Cumulative Nitrogen and Phosphorus Loads in Runoff from the Small Plots Receiving Various Poultry Litter Treatments During the First and Second Rainfall Simulations.

Treatment	SRP+ (kg/ha)	TP (kg/ha)	NO_3-N (kg/ha)	NH_4-N (kg/ha)	TN (kg/ha)
Pelleted Compost	0.0128 ab	0.0143 ab	0.0011 b	0.0143 ab	0.0437 ab
Pelleted Litter	0.0066 ab	0.0071 ab	0.0002 cb	0.0069 ab	0.0181 ab
Raw Litter	0.0042 bc	0.0046 bc	0.0004 b	0.0032 b	0.068 b
No Poultry Litter	0.0014 d	0.0015 d	0.0001 cb	0.0002 c	0.0012 c
Alum Litter	0.0023 cd	0.0031 cd	0.0002 cb	0.0188 ab	0.0261 ab
Pelleted Alum	0.0048 abc	0.0056 abc	0.0002 cb	0.0165 a	0.0278 a
Normal Litter	0.0119 a	0.0129 a	0.0051 a	0.0150 a	0.0291 a

Notes: Data represent mean of four replicates.
+Different letters within a column denote significant differences between cumulative nutrient loads during the first and second runoff event.

litter treatments, including the plots not receiving poultry litter applications.

DISCUSSION

Phosphorus Transfer in Runoff From Plots

Reducing P solubility in poultry litter is an effective means to mitigate P losses to surface waters because when poultry litter is applied to the landscape, the amount of WEP in the poultry litter applied was often an important determinant in P concentrations in the runoff water (Sauer *et al.,* 2000; Kleinman *et al.,* 2002a; DeLaune *et al.,* 2004). This study showed a positive correlation between WEP application rates of the various poultry litters and P concentrations in the runoff from small plots (Figure 1), providing further evidence of the importance of the WEP content in poultry litter when considering P transfer in runoff from the landscape. However, it appears that WEP applied in the various poultry litters controls runoff P concentrations during the first runoff event, and this relation was not observed after one month. Furthermore, when poultry litter has not been recently applied to the landscape, manure P sources decrease in importance whereas soil P sources do not fluctuate in importance (McDowell and Sharpley, 2001). For example, Eghball *et al.* (2002) noted that P concentrations were significantly different between manure and no-manure plots when manure was recently applied; however, a year after manure application, no differences were observed in P concentrations. Phosphorus concentrations in runoff from small plots often display a decreasing exponential relation with time since poultry litter was applied (DeLaune *et al.,* 2004), but this relation may not be observed on the field scale (Moore *et al.,* 2000; Vories *et al.,* 2002) likely resulting from potential interactions between P concentrations, sediment loss, and surface runoff timing, volume and discharge. In this study, a large natural rainfall event (1,100 mm) occurred between artificial simulations, and P concentrations in runoff during the second rainfall simulation were greatly reduced but still significantly greater from plots receiving poultry litter than from plots without litter application.

Several previous studies on the laboratory- and field scales have shown reductions in P solubility in poultry litter when treated with alum (Moore and Miller, 1994; Moore *et al.,* 2000), as well as reductions in P concentrations in runoff water (Shreve *et al.,* 1995; Moore *et al.,* 2000). This investigation showed that alum additions to poultry houses in between flocks resulted in a significant reduction in P transfer in runoff from small plots receiving equivalent TP

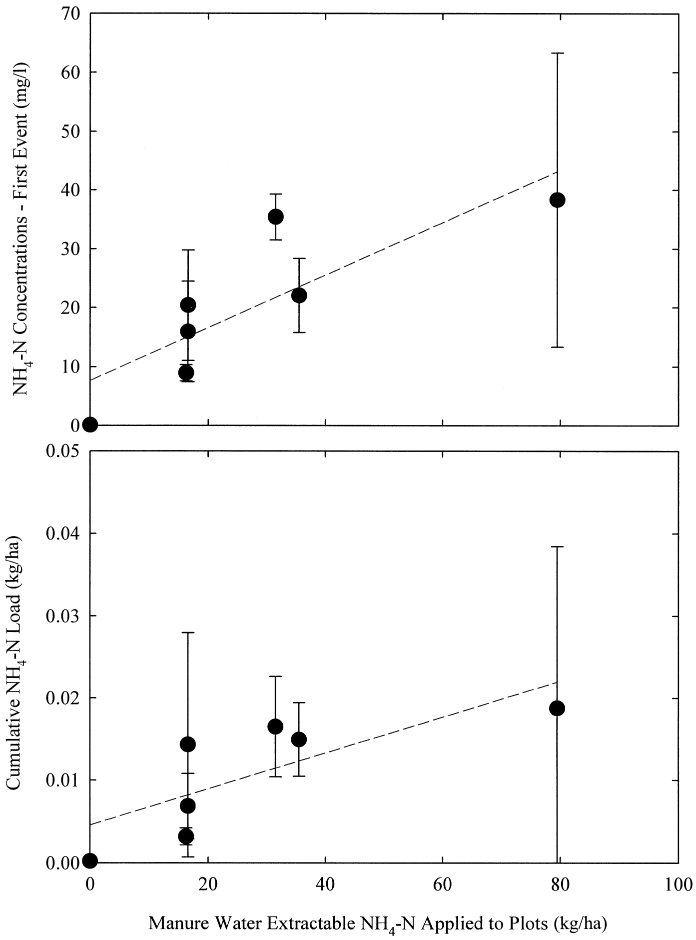

Figure 2. Effect of Application Rate of Water Extractable NH_4 in the Various Poultry Litters on NH_4 Concentrations (top) and Cumulative Load (bottom) in the Runoff from the Rainfall Simulations.

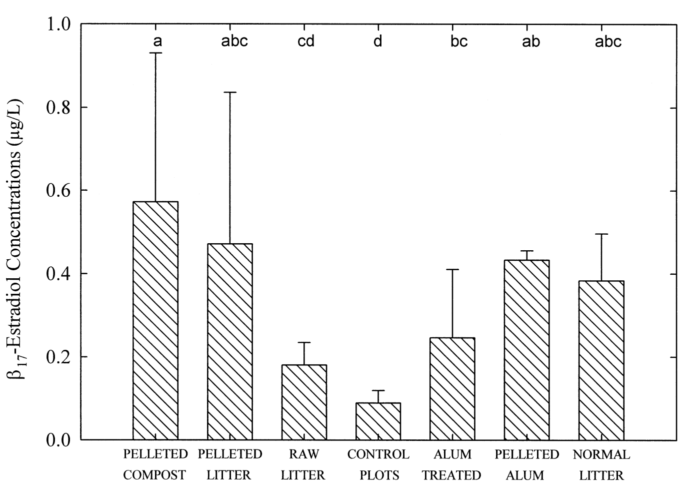

Figure 3. β_{17}-Estradiol Concentration in Runoff From Small Plots Receiving the Various Poultry Litter Treatments During the First Rainfall Simulation. (Letters indicate significant differences in β_{17}-estradiol concentration.)

based application rates (approximately 67 kg/ha) of poultry litters. Recently, alum standards as a best management practice to reduce P solubility in poultry litter and P transfer in runoff water have been promulgated by the several state cooperative extension services (e.g., Arkansas and Tennessee) and the USDA Natural Resources Conservation Service.

In this study, very high P concentrations (greater than 15 mg/l) were observed in runoff during the first rainfall simulation from normal litter, pelleted compost, and pelleted litter, reflecting the worst case scenario of having a surface runoff event immediately following land application. These high P concentrations in runoff occurred concomitant with elevated levels of WEP content in the various poultry litters. Pelleted compost and pelleted litter had significantly greater WEP content than the normal litter, but P concentrations in the runoff were similar between these treatments. The pelleted treatments also had significantly greater WEP content than raw litter, although this comparison should be interpreted cautiously because the raw and pelleted poultry litters may have been produced by birds grown under substantially different management and diets. However, pelleted alum had significantly greater WEP content and P concentrations in runoff compared to alum litter, and these results can be directly compared to infer pelleting increases WEP because alum litter was pelleted. Overall, these results suggested that some consideration needs to be given to the environmental effects of pelleting poultry litters, particularly a potential increase in P transfer in runoff when land applied. The range in WEP content from these poultry litters was similar to ranges reported in other studies in the Ozarks and other regions (Sims and Luka-McCafferty, 2002), and WEP content from the pelleted treatments was not outside this typical range.

The pelleting process provides some heat (80 to 90°C) (Gray, 1999) and pressure when forming pellets, and this may increase the solubility of organically bound P (e.g., phytate P, potentially increasing P transport in runoff). For example, Ajiboye *et al.* (2004) showed that oven drying manures can increase WEP by converting organic P to inorganic P. The intent of pelleting poultry litters will be to facilitate the transport of this resource out of sensitive catchments and to promote the use of organic fertilizers as an alternative to commercial inorganic fertilizers. The use of pelleted manure in row crops (e.g., see Wang *et al.,* 2001; Kato *et al.,* 2002) and urban areas has shown some significant benefits as an alternative to commercial fertilizers. Furthermore, the pelleting process may provide some other environmental benefits, such as reducing pathogenic microbes.

Nitrogen Transfer in Runoff From Plots

The pelleted poultry litters did not display any distinct differences in water extractable or total N content nor in soluble or total N concentrations in the runoff similar to those observed with P. Transfer of N in runoff from plots receiving pelleted compost or pelleted litter generally had a greater fraction of organic N compared to the dissolved inorganic form. On the other hand, most N transfer in runoff from alum litter was in the NH_4 form. The application rate of water extractable NH_4 in the various poultry litters was variable (16 to 80 kg/ha) and was strongly correlated to NH_4 concentrations in runoff. It is difficult to ascertain differences between treatments in N loss from the various poultry litters because TN application rates varied from about 150 to 250 kg/ha, while TP application rates were constant among treatments. However, alum litter generally had the greatest NH_4 and TN content, as well as the greatest NH_4 and TN concentrations in runoff from the small plots. This result was not surprising, because application of alum between flocks at poultry houses may reduce NH_3 volatilization, thereby increasing the TN content of poultry litters (Moore *et al.,* 2000). The increase in TN content of the poultry litter has often resulted in an increase in forage production and forage N content when land applied in small plot studies (Shreve *et al.,* 1995). If these treatments had been applied at equivalent TN rates, then similar TN transfer in runoff may be expected from each treatment, whereas P transfer in runoff would likely be related to changes in WEP application rates with N based application of these poultry litters.

β_{17}-Estradiol Transfer in Runoff from Plots

Land application of poultry litter may represent a potential source of estrogens to surface waters, because poultry litter may contain from 14 to more than 500 mg/kg of estrogen in the litter (Shore *et al.,* 1993; Shore *et al.,* 1995). Runoff concentrations of β_{17}-estradiol measured in this study were less than 1 µg/l, and similar to those reported by Nichols *et al.* (1997) at similar land application rates of poultry litter. Alum addition between poultry flocks was an effective method of reducing the loss of β_{17}-estradiol from the landscape (Nichols *et al.,* 1997; DeLaune *et al.,* 2002), and this study provided further evidence supporting the ability of alum to reduce β_{17}-estradiol transfer in runoff. The mechanism with which alum reduces β_{17}-estradiol concentrations in runoff water is likely related to flocculation of organic compounds (e.g., see Moore *et al.,* 1997); runoff from plots treated with poultry litter often has less soluble organic carbon compared to untreated poultry litter. The effect of pelleting poultry litters on loss of organic compounds, particularly such as this hormone, are unclear given that the pelleted compost, pelleted litter and raw litter may be from birds under different management and diets. For example, DeLaune *et al.* (2002) observed variable β_{17}-estradiol concentrations in runoff from small plots receiving poultry litter from birds fed different diets.

The persistence of β_{17}-estradiol after land application has been observed in runoff samples one week after land application in a previous study (Nichols *et al.,* 1997). β_{17}-estradiol may show an exponential decline in concentrations in runoff with time since application (DeLaune *et al.,* 2002). This study showed that concentrations from poultry litter amended plots were similar to those without any poultry litter application in about 30 days, likely because of the large natural rainfall in between simulation. DeLaune *et al.* (2002) observed measurable differences between poultry litter treated (6 Mg/ha) plots and plots without any litter treatment 20 days after application, where concentrations were less than half that measured in runoff immediately following litter application. A recent study has shown that β_{17}-estradiol in soils was readily transformed to estrone and suggested that estrone should be included when analyzing for estrogenic compounds (Colucci *et al.,* 2001).

CONCLUSIONS

The addition of nutrients to small plots via surface application of various poultry litters significantly increased nutrient and β_{17}-estradiol concentrations in runoff water during rainfall simulations. Transfer of NH_4 and P in runoff was strongly correlated to the amount of water extractable NH_4 and P applied in the various poultry litters, supporting several recent investigations. Thus, best management practices that focus on reducing WEP in poultry litter will reduce P losses when the poultry litter is surface applied to pastures. Alum additions to poultry litter effectively reduced WEP concentrations in the litter itself and also P concentrations in runoff from the small plots.

Alum additions to poultry houses between flocks provides many other benefits including reduced NH3 volatilization, increased weight gains, and decreased energy expenditures. β_{17}-estradiol concentrations are generally reduced by alum additions, whereas N losses may increase in surface runoff because of an increase in TN content resulting from reduced NH_3 volatilization. However, the use of alum in poultry houses does not address the issue of P accumulation in soils and should be viewed as a short-term solution to P management. The real issue with respect to P in agriculture is farm scale imbalances, and economical transport of poultry litter to other lands suitable for forage and crop production.

Some distinct differences were observed in N, P, and β_{17}-estradiol concentrations in runoff from the plots treated with the various poultry litters. These results suggested that pelleting poultry litters may increase the potential for P transfer in runoff, particularly because of an increase in the amount of WEP in the pelleted product. However, these inferences regarding pelleted poultry litters should be interpreted cautiously because the poultry litters may have been from birds under different management and diets, but the pelleted alum and alum litter were from the same source. Thus, the environmental consequence of pelleting poultry litters needs additional investigation, particularly related to P solubility and pasteurization of pathogenic microbes. Furthermore, N, P, and β_{17}-estradiol transfer from poultry litters to surface runoff is just as much a function of application rates and timing as it is a function of how the poultry litter is managed and treated.

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LITERATURE CITED

Ajiboye, B., O.O. Akinremi, and G.J. Racz. 2004. Laboratory Characterization of Phosphorus in Fresh and Oven-Dried Organic Amendments. Journal of Environmental Quality 33:1062-1069.

APHA (American Public Health Association), 1992. Standard Methods for Analysis of Waters and Wastewaters. American Public Health Association, Washington, D.C..

Analytical Software, 2003. Statistix 8.0 Analytical Software. Tallahassee, Florida.

Carpenter, S.R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V.H. Smith, 1998. Nonpoint Pollution of Surface Waters With Phosphorus and Nitrogen. Ecological Applications 8:559-568.

Chaubey, I., D.R. Edwards, T.C. Daniel, P.A. Moore Jr., and D.J. Nichols, 1995. Effectiveness of Vegetative Filter Strips in Controlling Losses of Surface Applied Poultry Litter Constituents. Transactions of the American Society of Agricultural Engineers 38:1687-1692.

Colborn, T., F.S. vom Saal, and A.M. Soto, 1993. Developmental Effects of Endocrine-Disrupting Chemicals in Wildlife and Humans. Environmental Health Perspectives 101:378-381.

Colucci, M.S., H. Bork, and E. Topp, 2001. Persistence of Estrogenic Hormones in Agricultural Soils: I. 17b-Estradiol and Estrone. Journal of Environmental Quality 30:2070-2076.

Davis D.L. and H.L. Bradlow, 1995. Can Environmental Estrogens Cause Breast Cancer? Scientific American 273:166-172.

DeLaune, P.B., P.A. Moore, Jr., D.K. Carmen, A.N. Sharpley, B.E. Haggard, and T.C. Daniel, 2002. Using the Phosphorus Index to Reduce Phosphorus Runoff From Soils in the Eucha/Spavinaw Watershed. Final Report, City of Tulsa, Oklahoma, USA, 277 pp.

DeLaune, P.B., P.A. Moore, Jr., D.K. Carmen, A.N. Sharpley, B.E. Haggard, and T.C. Daniel, 2004. Development of a Phosphorus Index for Pastures Fertilized With Poultry Litter – Factors Affecting Phosphorus Runoff. Journal of Environmental Quality 33:2183-2191.

Edwards, D.R., and T.C. Daniel, 1992. Potential Runoff Quality Effects of Poultry Manure Slurry Applied to Fescue Plots. Transactions of the American Society of Agricultural Engineers 35:1827-1832.

Edwards, D.R., and T.C. Daniel. 1993. Effects of Poultry Litter Application Rate and Rainfall Intensity on Quality of Runoff From Fescuegrass Plots. Journal of Environmental Quality 22:361-365.

Eghball, B., J.E. Gilley, D.D. Baltensperger, and J.M. Blumenthal, 2002. Long-Term Manure and Fertilizer Application Effects on Phosphorus and Nitrogen in Runoff. Transactions of the American Society of Agricultural Engineers 45:687-694.

Gburek, W.J., A.N. Sharpley, L. Heathwaite, and G.J. Folmar, 2000. Phosphorus Management at the Watershed Scale: A Modification of the Phosphorus Index. Journal of Environmental Quality 27:267-277.

Gray, K., 1999. Turning Poultry Litter Into Fertilizer Products. Biocycle 40:49-50.

Haggard, B.E., P.A. Moore, Jr., I. Chaubey, and E.H. Stanley, 2003. Nitrogen and Phosphorus Concentrations and Export From an Ozark Plateau Catchment in the United States. Biosystems Engineering 86:75-85.

Hirsch, R.M., R.B. Alexander, and R.A. Smith, 1991. Selection of Methods for the Detection and Estimation of Trends in Water Quality. Water Resources Research 5:803-813.

Kato, M., Y. Kaneta, and H. Shindo, 2002. Effects of Pellet Manure and Fertilizer on Growth and Yield of Rice. Japanese Journal of Crop Science 45:39-41.

Kleinman, P.J.A., A.N. Sharpley, B.G. Moyer, and G.F. Elwinger, 2002a. Effect of Mineral and Manure Phosphorus Sources on Runoff. Journal of Environmental Quality 31:2026-2033.

Kleinman, P.J.A, A.N. Sharpley, A.M. Wolf, D.B. Beegle and P.A. Moore, Jr., 2002b. Measuring Water-Extractable Phosphorus in Manure as an Indicator of Phosphorus in Runoff. Soil Science Society of America Journal 66:2009-2015.

Kolpin, D.W., E.T. Furlong, M.T. Meyer, E.M. Thurman, S.D. Zaugg, L.B. Barber, and H.T. Buxton, 2002. Pharmaceuticals, Hormones, and Other Organic Wastewater Contaminants in U.S. Streams, 1999-2000: A National Reconnaissance. Environmental Science and Technology 36:1202-1211.

Lemunyun, J.L. and R.G. Gilbert, 1993. Concept and Need for a Phosphorus Assessment Tool. Journal of Production Agriculture 6:483-486.

Lettenmaier, D.P., E.R. Hooper, C. Wagner, and K.B. Faris, 1991. Trends in Stream Quality in the Continental United States, 1978-1987. Water Resources Research 27:327-339.

McDowell, R.W. and A.N. Sharpley, 2001. Approximating Phosphorus Release From Soils to Surface Runoff and Subsurface Drainage. Journal of Environmental Quality 30:508-520.

Mehlich, A., 1984. Mehlich 3 Soil Test Extractant: A Modification of Mehlich 2 Extractant. Communications in Soil Science and Plant Analysis 15:1409-1416.

Moore, Jr., P.A., T.C. Daniel, and D.R. Edwards, 2000. Reducing Phosphorus Runoff and Inhibiting Ammonia Loss From Poultry Manure With Aluminum Sulfate. Journal of Environmental Quality 29:37-49

Moore, Jr., P.A., B.E. Haggard, T.C. Daniel, D.R. Edwards, B.R. Shreve, and T.J. Sauer, 1997. Demonstration of Nutrient Management for Poultry Litter Using Alum Precipitation of Soluble Phosphorus. Final Report, Region VI, U.S. Environmental Protection Agency, Task 92-500.

Moore, Jr., P.A. and D.M. Miller, 1994. Decreasing Phosphorus Solubility in Poultry Litter With Aluminum, Calcium and Iron Amendments. Journal of Environmental Quality 23:325-330.

Nichols, D.J., T.C. Daniel, P.A. Moore, Jr., D.R. Edwards, and D.H. Pote, 1997. Runoff of Estrogen Hormone 17β-Estradiol From Poultry Litter Applied to Pasture. Journal of Environmental Quality 26:1002-1006.

Petersen, E.W., R.K. Davis, and H.A. Orndoff, 2000. 17β-Estradiol as an Indicator of Animal Waste Contamination in Mantled Karst Aquifers. Journal of Environmental Quality 29:826-834.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols, 1996. Relating Extractable Soil Phosphorus to Phosphorus Losses in Runoff. Soil Science Society of America Journal 60:855-859.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.M. Miller, and D.R. Edwards, 1999. Relationship Between Phosphorus Levels in Three Ultisols and Phosphorus Concentration in Runoff. Journal of Environmental Quality 28:170-175.

Sauer, T.J., T.C. Daniel, D.J. Nichols, C.P. West, P.A. Moore, Jr., and G.L. Wheeler, 2000. Runoff Water Quality From Poultry Litter-Treated Pasture and Forest Sites. Journal of Environmental Quality 29:515-521.

Self-Davis, M.L. and P.A. Moore, Jr., 2000. Determining Water Soluble Phosphorus in Animal Manure. *In:* Methods of Phosphorus Analysis in Soils, Sediments, Residuals and Waters, G.M. Pierzynski (Editor). Southern Cooperative Series Bulletin No. 396, North Carolina State University, Raleigh, North Carolina.

Sharpe, R.M. and N.E. Skakkebaek, 1993. Are Oestrogens Involved in Falling Sperm Counts and Disorders of the Male Reproductive Tract? The Lancet 341:1392-1395.

Sharpley, A.N., S.J. Smith, and W.R. Bain, 1993. Nitrogen and Phosphorus Fate From Long-Term Poultry Litter Applications to Oklahoma Soils. Soil Science Society of America Journal 57:1131-1137.

Shore, L.S., D.L. Correll, and P.K. Chakraborty, 1995. Relationship of Fertilization With Chicken Manure and Concentrations of Estrogens in Small Streams. *In:* Animal Waste and the Land-Water Interface, K. Steele (Editor). CRC Lewis Publishers, New York, New York.

Shore, L.S., E. Harel-Markowitz, M. Gurevich, and M. Shemesh, 1993. Factors Affecting the Concentration of Testosterone in Poultry Litter. Journal of Environmental Science and Health A28:1737-1749.

Shreve, B.R., P.A. Moore, Jr., T.C. Daniel, D.R. Edwards, and D.M. Miller, 1995. Reduction of Phosphorus in Runoff From Field-Applied Poultry Litter Using Chemical Amendments. Journal of Environmental Quality 24:106-111.

Sims, J.T. and N.J. Luka-McCafferty, 2002. On-Farm Evaluation of Aluminum Sulfate (alum) as a Poultry Litter Amendment: Effects of Litter Properties. Journal of Environmental Quality 31:2066-2073.

Vadas, P.A., P.J.A. Kleinman, and A.N. Sharpley. 2004. A Simple Method to Predict Dissolved Phosphorus in Runoff From Surface-Applied Manures. Journal of Environmental Quality 33:749-756.

Vories, E.D., T.A. Costello, and R.E. Glover, 2002. Runoff From Cotton Fields Fertilized With Poultry Litter. Transactions of the American Society of Agricultural Engineers 44:1495-1502.

Wang, Y., K. Yamamoto, K. Yakushido, and W. Yan, 2001. Nitrogen Release From Livestock Waste Compost Pellets in Barley Fields. Japanese Journal of Soil Science and Plant Nutrition 47:675-683.

Zarcinas, B.A., B. Cartwright, and L.R. Spouncer, 1987. Nitric Acid Digestion and Multi-Element Analysis of Plant Material by Inductively Coupled Argon Plasma Spectrometry. Communications in Soil Science and Plant Analysis 18:131-146.